Analysis of Operational Strategies of a SOFC/MGT Hybrid Power Plant

Martina Hohloch*, Andreas Huber, Manfred Aigner
German Aerospace Center (DLR), Institute of Combustion Technology
Pfaffenwaldring 38-40
70569 Stuttgart, Germany
Email: martina.hohloch@dlr.de

ABSTRACT

The present work deals with the analysis of operational concepts for a SOFC/MGT hybrid power plant based on a test rig at the DLR, Institute of Combustion Technology. Here, a Turbec T100 micro gas turbine and a fuel cell emulator are used. The emulator is composed of two pressure vessels. The first represents the cathode volume of the fuel cell to simulate the residence time and pressure loss. The second is equipped with a natural gas combustor to emulate the varying heat input of the fuel cell. The MGT and the SOFC are connected via different piping paths.

The procedures start-up, load change and shutdown are analyzed in matters of temperature gradients, pressure gradients and fluctuations, as well as the air mass flow provided at the interconnections to the coupling elements. To achieve the required inlet conditions of the SOFC, transient operations, using the different piping paths, are investigated. Concepts for heating-up and cooling the SOFC using hot air from the recuperator and relatively cold air from the compressor outlet are experimentally tested and characterized. Selected critical situations and their effect on the SOFC are investigated. An emergency operation, its impact on both subsystems and limitations are shown. Further operational limits of the MGT control system and power electronic were observed and analyzed. Based on the experimental results, the applicability of the used MGT procedures in a hybrid power plant was reconsidered. Finally, adaptions and strategies for the operational concept are derived and discussed.

Keywords: hybrid power plant test rig, MGT, SOFC emulator

Nomenclature

abs absolute
DLR German Aerospace Center
e electrical
G generator
Hypp hybrid power plant
MGT micro gas turbine
PE power electronic
rel relative
SOFC solid oxide fuel cell
TIT turbine inlet temperature
TOT turbine outlet temperature
Δp pressure loss
Δp_{rel} relative pressure loss between compressor and turbine inlet in relation to compressor outlet pressure
ε recuperator efficiency
Π_{comp} compressor pressure ratio
h relative humidity
mf mass flow
mf_{air} air mass flow

*Address all correspondence to this author.

$mf_{air,\,SOFC}$ air mass flow to the SOFC
$mf_{bleed\ air}$ air mass flow on the bleed air path
mf_{main} fuel mass flow to main stage
N turbine speed
p pressure
$p_{comp,\,in}$ compressor inlet pressure
$p_{comp,\,out}$ compressor outlet pressure
$p_{SOFC,\,in}$ SOFC inlet pressure
$p_{turb,\,in}$ turbine inlet pressure
T temperature
t time
$T_{comp,\,in}$ compressor inlet temperature
$T_{comp,\,out}$ compressor outlet temperature
$T_{piping\ system,\,in}$ air temperature at inlet to piping system
$T_{rec,\,air,\,out}$ air temperature at the recuperator outlet
$T_{SOFC,\,in}$ temperature at SOFC inlet
$T_{SOFC,\,out}$ temperature at SOFC outlet
x_i corrected mass flow

1 INTRODUCTION

Hybrid power plants, based on a combination of a solid oxide fuel cell (SOFC) and a micro gas turbine (MGT), are a promising concept to face the demands of future power generation in terms of efficiency, emissions and flexibility. The power plants can be used as a central power station as well as a distributed power plant. The combination of a fuel cell and a gas turbine can be implemented in different arrangements. In the presented study, a solid oxide fuel cell (SOFC) is integrated into the micro gas turbine cycle between the compressor and the turbine. In this concept, the SOFC uses pressurized air supplied by the MGT to increase both power density and electric efficiency, significantly reducing the SOFC stacks needed for the given power output. Additionally, the MGT benefits from the heat input of the SOFC exhaust gases to produce additional power while using no or little additional fuel. With this power plant concept, depending on the size, electrical efficiencies up to 70 % can be reached. For decentralized power generation in the range of $\leq 100\,kW_e$, even 60 % efficiency are feasible. Besides the adequate matching and an effective integration of the subsystems, MGT and SOFC, the main challenges in the realization of such a power plant concept are the development of a stable and robust operational strategy. It requires a deep understanding of the impact of both main subsystems on each other as well as the impact of the connecting elements.

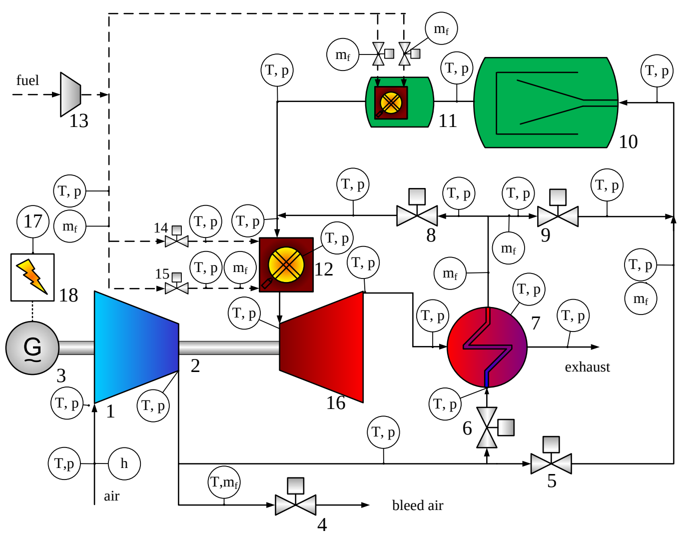
The present work is based on the experiences of Siemens Westinghouse and their SOFC concept. However, the results can be applied to different SOFC systems. The Siemens Westinghouse hybrid power plant demonstrator was built in Co-operation with California Edison Company and the United States Department of Energy [1]. A 1152 tubular cell SOFC was coupled to a modified two stage Ingersoll-Rand MGT. In this configuration, the SOFC could reach an electrical power output of 175 kW at a pressure ratio of 4:1. The MGT only reached 20 kW in maximum. The demonstrator was operated at the University of California, Irvine with some interruptions due to problems with the fuel cell and the MGT [2, 3]. Finally, the power plant reached an accumulated operation time of more than 3000 hours. The demonstrator was shut down due to problems with the fuel cell. The second demonstrator consisted of a Turbec T100 MGT with an electrical power output of 100 kW coupled to a tubular SOFC with 1704 cells. The demonstrator was designed to reach 300 kW electrical power output. Unfortunately, during factory acceptance tests, it was found that there was a leakage problem inside the fuel cell that led to a low power output. Due to an extensive estimated effort for re-design and re-build, the project was canceled. Nonetheless, Siemens Westinghouse displayed the feasibility of the hybrid concept with these first demonstrators. By those experiences they stated the need for further development regarding the components and their integration. Siemens Westinghouse summarized the characteristics for a micro gas turbine to be coupled to a SOFC from a fuel cell manufacturers point of view. The main requirement was a MGT with flexible turbine speed adapted in size to meet the amount of air to the SOFC in different operation modes, which is necessary for an active SOFC stack temperature control. The investigation of pressurization of fuel cells showed that the desired pressure ratio should be in the range of 3:1 to 4:1. The turbine inlet temperature should range between 820 °C to 950 °C, combined with a high-effectiveness recuperator ($\varepsilon \geq 90\,\%$). Furthermore, the combustor should be capable of high inlet temperatures between 820 °C to 870 °C with a wide fuel flow modulation range. Additional specifications include a variable high-speed alternator with associated electronics, continuous operation during loss-of-grid events and a turbine generator motoring capability [4].

The Institute of Combustion Technology (VT) and the Institute of Engineering Thermodynamics (TT) at the German Aerospace Center (DLR) have been collaborating since 2006 to develop a real coupled demonstrator. The chosen hybrid power plant configuration consists of a Siemens tubular SOFC and a Turbec T100PH MGT. In the first phase, the subcomponents SOFC and MGT were analyzed separately [5, 6]. For the coupling of both systems and the development of a control system, it is important to understand the influence of necessary coupling elements on each sub-component and to analyze the mutual interaction. Thus, a test rig was built for the characterization of the MGT under hybrid conditions. Therefore, the Turbec T100PH was coupled via a piping system to a SOFC emulator instead of a real fuel cell. The emulator is capable of simulating the thermodynamic and fluid dynamic properties of a real fuel cell. In [5] and [6] the hybrid power plant test rig and the underlying micro gas turbine test rig were described and the characterization of the standard MGT configuration was shown. In a next step the behavior of the micro gas turbine in hybrid conditions was compared to the standard MGT. In [7] the influence of the coupling elements (piping system, flaps and valves) on the MGT was investigated. Due to the high complexity of the system, the coupling was done stepwise, starting from the MGT connected to the piping system to the fully equipped test rig in different configurations. The behavior and the characteristics in those different configurations was analyzed in [8]. The main focus of the study was set on the achieved operational area of the test rig and different influencing factors on the operation. Based on those previous investigations, the influence of a hybrid power plant on the MGT and the resulting operational area of such an arrangement could be identified and analyzed. Beside the DLR hybrid power plant test rig, the National Energy Technology Laboratory (NETL) in Morgantown (USA) [9] and the University of Genoa (Italy) [10] developed so called ”hybrid system emulators”. A detailed description of the differences among each other and the DLR test rig is given in [8].

For the development of a hybrid power plant control system it is essential to know the provided inlet conditions from one subsystem to the other and mutual interactions. Therefore, this paper focuses on the investigation and discussion of the conditions at the interfaces from the micro gas turbine to the SOFC in all relevant transient operations in respect to the boundary conditions of a Siemens Westinghouse SOFC. Required changes and optimizations to the micro gas turbine control system and the hybrid control concept are also discussed.

2 EXPERIMENTAL SETUP

2.1 Hybrid Power Plant Test Rig



1 compressor
2 shaft
3 generator
4 bleed air valve
5 SOFC cold air control valve
6 recuperator bypass control valve
7 recuperator
8 SOFC bypass control valve
9 SOFC hot air control valve
10 pressure vessel incl. installations
11 pressure vessel incl. gas preheater
12 combustor
13 fuel compressor
14 pilot valve
15 main valve
16 turbine
17 turbine control system
18 power electronic

Fig. 1 Scheme and instrumentation of the applied hybrid power plant test rig setup

The DLR hybrid power plant test rig (Fig. 1) is described in detail in previous work [5–8]. Therefore, only a short description is presented here. The test rig is based on a commercially available Turbec T100PH micro gas turbine series 3 with a modified 2007-version control system using a booster. The T100 is a MGT with an electrical power output of 100 kW at a maximum pressure ratio of 4.5:1. Connected to the grid, the MGT can be operated at different turbine speeds from 75 % to 100 %, where 70,000 rpm represents full speed. The turbine outlet temperature is maintained constant at 645 °C. With the adapted control system, either a speed demand or an electrical power output demand can be given and the TOT can be adjusted between 360 °C and 655 °C. The MGT design offers the possibility to integrate the SOFC between recuperator and combustion chamber. The SOFC concept is based on a Siemens tubular solid oxide fuel cell. Instead of a real fuel cell, an emulator is used. Both subcomponents are coupled using different piping paths. The cold-air path connects the SOFC to the compressor outlet. During standard operation, the preheated air from the recuperator outlet is fed to the SOFC inlet via a hot-air path. A bypass line leads the air from the recuperator directly to the MGT combustion chamber. The mass flow through the different sections is controlled via flaps and valves.

2.2 Instrumentation

The test rig is equipped with detailed instrumentation, as shown in Fig. 1. With a total of 110 type N and K thermo-

Parameter	Accuracy	Unit
T	$\pm 0,85$	%
p	± 4	mbar
mf fuel total	± 0.4	%
mf fuel main	± 0.2	g/s
mf air	-	-
mf bleed air	± 1	%

Table 1 Accuracy of measurement system

couples of precision class 1 and 2, the temperatures in the system are monitored. An "Esterline Pressure Scanner" (model 9116) is used to measure total and static pressures at 51 points, whereas ambient pressure is measured using a model 9032 pressure scanner. The air mass flow is measured using "SKI SDF" flow rate sensors. The total fuel mass flow is detected via an "Endress + Hauser Promass 83F" and the fuel mass flow to the main stage is detected via a "Bronkhorst Cori-Flow" sensor. Except for the pressure, all analogue and digital inputs were sampled using a "Delphin" data acquisition system at a sampling rate of 2 Hz. The measurement accuracies can be found in Table 1.

2.3 SOFC Emulator

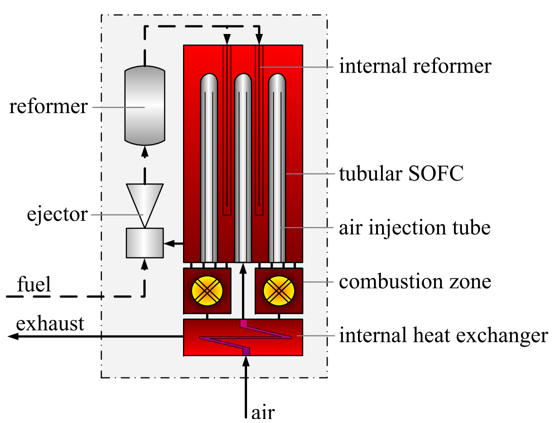


Fig. 2 Selected tubular SOFC concept

In Fig. 2, a schematic drawing of a tubular fuel cell system is shown. The air enters the stack through an internal heat exchanger, where it is further preheated. Through the air injection tube, air is fed into the fuel cell. Via the ejector, the fuel flows first to an external reformer before it enters the internal reformer. Then, the fuel is directed around the fuel cell tubes. A part of the fuel is recirculated using the ejector. In the post combustion zone, the fuel reacts with the depleted air and leaves the system through the heat exchanger. Based on this system, Panne et. al. [11] showed in his studies, using an in-house simulation tool [12], the dimensioning of the fuel cell size, which was used for the DLR concept. The study identified three limitations for the selection of the stack, which include the maximum compressor pressure ratio, the SOFC air bypass and the additional natural gas mass flow used in the combustion system of the gas turbine. Within the resulting operational area, a stack size of 1152 cells was chosen to generate a noteworthy influence of the SOFC and to ensure a wide operational area. Within the hybrid power plant test rig, only the cathode side of the SOFC can be emulated. The two pressure vessels (shown in Fig. 1) have a total volume of approximately 1.9 m^3 and represent the volume of the cathode side, the post combustor and the heat exchanger. In the second pressure vessel, a two stage natural gas combustor with a main stage based on the FLOX® principle and a swirl stabilized pilot stage is implemented. With this arrangement the outlet temperature of the SOFC after the internal heat exchanger can be emulated. The specified temperature range by Siemens Westinghouse between 820 °C to 870 °C can be reached.

3 RESULTS

For the analysis of the operational strategies, the fully equipped test rig as shown in Fig. 1 was used. As the focus of this characterization is on the inlet conditions of the SOFC provided by the MGT, mainly parameters affecting the SOFC directly are shown and analyzed.

3.1 Start-up

The start-up procedure illustrates the basic differences between the two subsystems, MGT and SOFC. The MGT is able to start-up within minutes and is completely heated up within approximately 1.5 hours. On the contrary, the SOFC heating process is limited due to a temperature gradient limit of 5 to 10 K/min (depending on the SOFC manufacturer this value may change). The micro gas turbine increases speed and the pressure in the system within seconds. The SOFC requires a smooth pressure control to ensure a minimum pressure difference between the anode and cathode side. A sudden pressure drop bears the risk of exceeding the maximum allowed pressure difference between the anode and cathode side. Different possibilities in starting the hybrid power plant were already discussed in [7]. Consequentially, it was decided to start the MGT first mechanically coupled but thermally separated. During the start-up, the SOFC is pressurized due to the mechanically coupling with the piping system, however no air is fed through the SOFC. Therefore, the bypass path is used. As soon as the temperature rises, the anode side has to be purged with forming gas (a mixture of 95 % nitrogen and approximately 5 % hydrogen) to prevent the oxidation of the anode. The SOFC is then preheated after MGT start-up using the cold-air path and hot-air path, while adapting the air mass flow to ensure the allowed temperature gradients. This approach is in general feasible but can be optimized. Therefore, the procedure is analyzed in the following section, possible adaptions are discussed and an alternative approach is given.

MGT Start-up For the start-up of the MGT, the standard procedure is used. To assess this procedure, the temperature at the interfaces to the piping system, the pressure in the system and the total air mass flow are considered and shown in Fig. 3. The MGT starts by accelerating the shaft to a turbine speed of 34 %. At this point, the temperature in the piping system is still on ambient level with a value of 23 °C, whereas the temperature at the compressor outlet is already at 40 °C. After the ignition of the MGT combustor, the temperature at the inlet to the piping system increases with a mean gradient of 26 K/min. During the ramp-up from ignition speed to the demanded speed of 75 %, the gradient increases temporarily due to the ascending overlain heat of compression. The compressor outlet temperature rises in this period up to 104 °C ($\Delta T / t$ = 41 °C / min). The gradient decreases and the temperature approximates to a value of 146 °C at the steady state load point. When a TOT of 645 °C is reached, the temperature gradient at the piping system inlet declines. In steady state conditions, a value of 585 °C is obtained. The air mass flow in the system mainly follows the turbine speed with some overshoots when speed levels of 34 % and 75 % are achieved. The pressure at different probes in the system mainly follows the turbine speed too. During ignition, there is a change in pressure. At 75 % turbine speed, the pressure further increases with increasing temperatures. During the ramp-up to ignition speed, a pressure gradient of 0.007 bar/s is seen. During the second ramp-up, a mean gradient of 0.013 bar/s in pressure and 3.1 (g/s)/s in air mass flow is seen. Fluctuations occur in the turbine inlet pressure when the demanded turbine speed is reached. The fluctuations are based on irregularities in the control of the fuel to the main combustor. It was observed in some cases that those instabilities led to fluctuations in turbine speed, resulting in pressure fluctuations through the system. The resulting pressure variations at the SOFC inlet were at maximum 0.03 bar and therefore, categorized as not critical. If ignition is not successful the turbine stops and the procedure is restarted again, resulting in a sudden drop down in pressure and mass flow when the shaft is stopped.

Summarizing the observations during the start-up procedure, the main challenges are the pressure gradients, followed by the temperature gradients at ramp-up. Theoretically, one solution could be to decrease the acceleration of the turbine speed during the ramps. Due to resonance frequencies at turbine speeds around 55 %, this critical speed range has to be surpassed quickly. Hence, the control system of the hybrid power plant needs to be able to deal with those pressure gradients for a pressure difference regulation between the anode and cathode side of the SOFC. For the optimization of this procedure, one

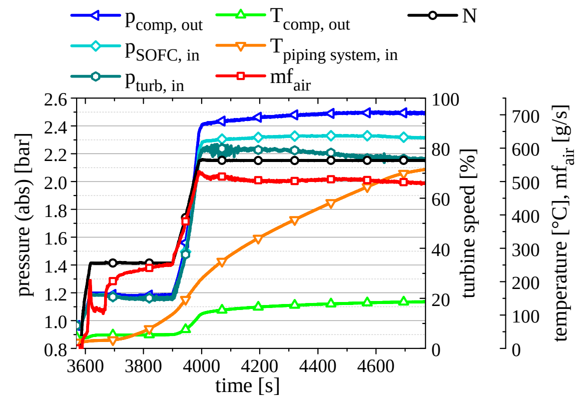


Fig. 3 MGT start-up to 75 % turbine speed

possibility is to start the system fully coupled and lead a part of the air mass flow through the SOFC cathode side. Therefore, operation at a turbine speed of 34 % has to be extended and a mixing temperature using the cold-air and hot-air paths to heat-up the SOFC to the temperature level of the compressor outlet in part load (146 °C) has to be adjusted. Consequently, it would be possible to perform the second ramp-up using the cold-air and bypass paths without modifications on the turbine control system and without exceeding the maximum temperature gradient of the SOFC. The amount of air through the SOFC could be adjusted using the bypass path. This concept has to be verified in further test campaigns.

SOFC Start-up After the MGT start-up process, the SOFC has to be heated to the operation temperature and the cathode air mass flow has to be adjusted to start the reaction. This is done by using the three different paths, cold-air, hot-air and bypass. The method shown in Fig. 4 was performed after the MGT start-up process using the bypass path. There was no temperature or air mass flow control implemented for the test. The valves and flaps were driven manually to analyze the influence on the SOFC inlet. The main focus is to achieve a monotonically increasing SOFC inlet temperature. The turbine speed was maintained constant at a value of 75 %. In Fig. 4, the different valve opening angles and the resulting temperature, pressure and air mass flow at the inlet to the SOFC are plotted against time. First the cold-air valve is opened at a constant speed to 60 % open. Thus, the mass flow to the SOFC increases. The mass flow trends display irregularities in comparison

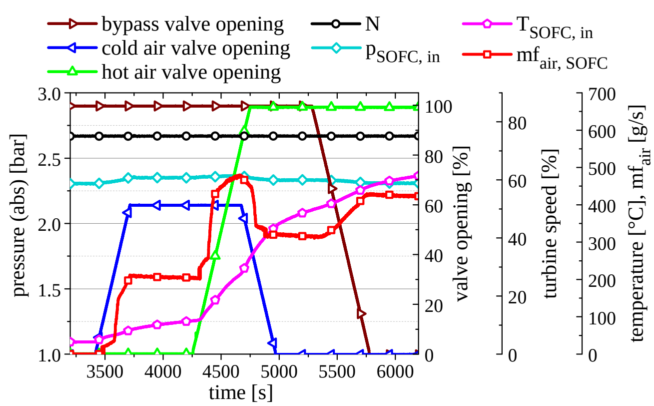


Fig. 4 Heating-up of SOFC using different paths

to the continuous valve opening mode. Below 32 % open, there is only a minor increase in mass flow, through the value between 32 % and 40 % the mass flow increases by 100 g/s and above 40 %, the mass flow gradient decreases back again to a lower level. These are basic characteristics of the valve which have to be implemented into the control system for air mass flow regulation. The temperature smoothly ascends and the pressure increases as the pressure drop in the system decreases. The opening of the cold-air valve is limited in the DLR hybrid power plant test rig to a value of 70 % due to a temperature limit downstream of the recuperator. As the cold-air path bypasses the MGT recuperator, the exhaust gas temperature of the plant increases. This also has to be taken into account for a real hybrid power plant, especially if a combined heat and power concept is integrated. Here, the water heat exchanger downstream of the recuperator needs to be able to handle outlet temperatures up to the temperature level of the TOT. As the temperature gradient at the of SOFC inlet starts to decrease, in the second step, the hot-air path is opened for further heating. A similar correlation between the valve opening angle and air mass flow can be observed. The temperature increases with a much larger gradient. The subsequent closing of the cold-air valve speeds up the temperature increase again but decreases the air mass flow. The closing of the bypass valve mainly affects the amount of air to the SOFC and further decreases the pressure. In both operations no predefined criterion was used for closing the valves. The aim was to analyze the switch over from heating mode to the operation mode, where only the hot-air path is used. During the whole heating method, no pressure disturbances are visible.

The method in this unregulated form is not applicable as the mass flow alternates too much and the temperature increase is unsteady. However, in general, it shows the feasibility of heating up the SOFC using the piping arrangement of the hybrid power plant test rig. For an applicable method, the opening of the cold-air and hot-air valves have to be controlled to reach a steady increase in mass flow to the specified value at the steady state load point. The bypass valve should be used in combination with the cold-air valve to maintain a nearly constant mass flow during the transition to the hot-air path. Finally, the gradients have to be adapted to the before mentioned maximum temperature gradient of 5 to 10 K/min.

MGT Hot-start-up A hot-start-up of the MGT is defined as a restart with high component temperatures. As for the MGT start-up the thermally and mechanically coupled approach is suitable with a minimum air mass flow to the SOFC. In some situations, it may be useful to perform such a hot-start-up of the MGT. For example, if the automatic mode causes a shut down of the facility due to a minor fault that can easily be reset. Another possible application is to use it in combination with a hot-stand-by mode. In general, this procedure is very similar to the normal start-up of the MGT. The main differences occur in the period of the single turbine states until steady state conditions are reached. In Fig. 5, the procedure is plotted against time. The temperatures in the system first decrease due to the restarting air mass flow through the system. In this

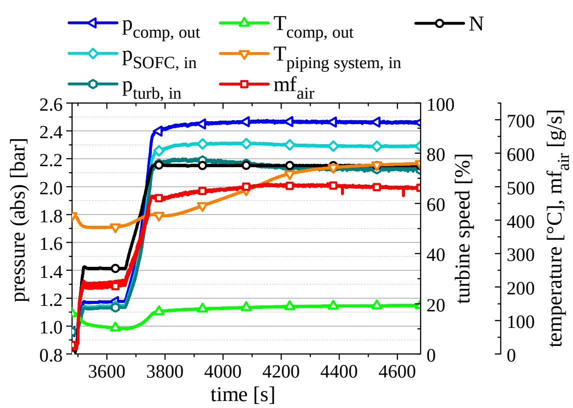
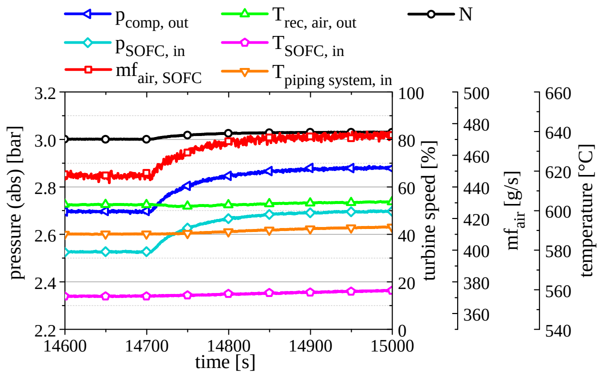


Fig. 5 MGT hot-start-up to 75 % turbine speed

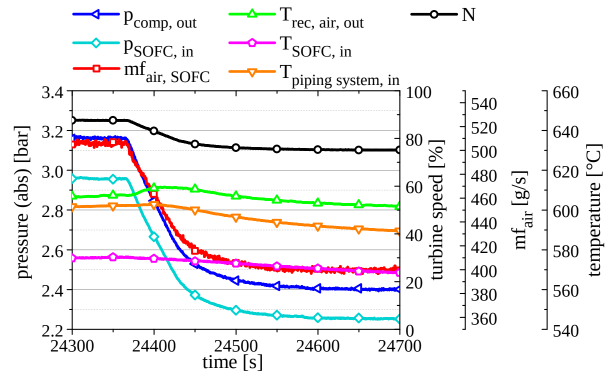
case, the temperature at the inlet to the piping system drops from 412 °C to 378 °C and at the compressor outlet from 120 °C to 75 °C. The condition for the beginning of the second ramp-up is reached much faster than in cold conditions. However, the ramp-up itself is the same as for the start-up in cold conditions. The gradients for both pressure and air mass flow do not vary between hot and cold conditions. The fluctuations in the pressure seen in the cold start-up and the overshoot in mass flow do not occur. Besides the successful execution of the procedure itself, a phenomena appears that has been described in [7]. After a hot start-up, the MGT operates at a slightly different load point with a lower surge margin and responds sensitively to any disturbances. This phenomena could not be sufficiently explained so far.

3.2 Load Changes

A MGT with flexible turbine speed allows for varying the shaft speed within certain limits. The chosen Turbec T100 ranges between 75 % to 100 %, which represents 52500 rpm to 70000 rpm. With the commercially available version, it is only possible to set a certain power output demand and the turbine speed is adjusted automatically by the MGT control system. For a hybrid power plant, it is more useful to adapt the turbine speed to control the air mass flow and the pressure. The MGT in the DLR hybrid power plant test rig is modified as already described in [7]. In addition to the turbine speed, the TOT can be varied between 360°C to 655°C. The achievable electrical power output is a result of these settings and depends on additional variables, like for example the ambient temperature. Fig. 6 shows two representative load changes of the MGT, resulting mainly in a change of mass flow and pressure at the inlet of the SOFC. In Fig. 6a, a load change from 80 % to 83 % turbine speed is shown. At the beginning, the shaft is accelerated with a gradient of 0.06 %/s, then slows down and slowly approaches the demanded speed of 83 %. This trend is also seen in the different pressure measuring points at the compressor outlet and SOFC inlet and in the air mass flow to the SOFC. The temperature at the recuperator outlet seems to decline during the procedure but as the load point is reached, it increases slightly. Due to the mass of the piping



(a) Load change from 80 % to 83 % turbine speed



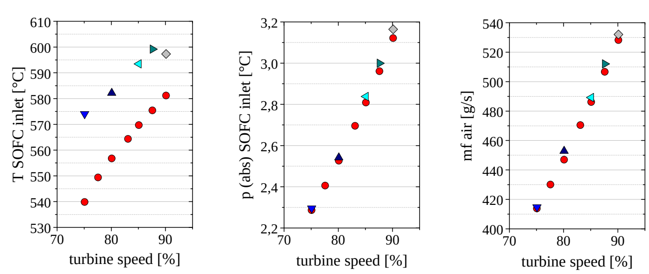
(b) Load change from 87.5 % to 75 % turbine speed

Fig. 6 MGT load changes

system, the temperature fluctuation is damped. At the SOFC inlet, the temperature increases very smoothly. Fig. 6b depicts a higher step in the turbine speed, from 87.5 % to 75 % turbine speed. The control system starts decreasing the turbine speed at a gradient of -0.14 %/s, then again slows down and slowly approaches 75 % turbine speed. The pressure and the air mass flow also follow the trend of the turbine speed. The load change causes a pressure change of 0.7 bar and a change in mass flow of approximately 107 g/s. During the procedure, the recuperator outlet temperature increases about 4°C and then declines. This overshooting is again not observed at the SOFC inlet. Here, the temperature decreases constantly with a gradient of 1.5 K/min. In both procedures, no fluctuations were observed at the SOFC inlet. For the control system, the pressure gradients for the anode pressure control have to be taken into account. Within the MGT control system the load change gradients can be easily adapted.

3.3 Operational Area

The operational area of a hybrid power plant is a result from the operating range of each subcomponent. Additional constraints arise from the impact of the mutual interaction of both systems and the necessary coupling elements. For the micro gas turbine, the operational area is given by the range of speeds and the required fuel input. It is affected by the SOFC and the coupling elements. The coupling elements represent supplemental pressure and heat loss, whereas the SOFC represents an additional pressure loss and a second heat source. The operational area of the MGT in the hybrid power plant test rig is already analyzed and discussed in [8]. In Fig. 7, the resultant inlet conditions to the SOFC provided by the MGT are plotted against the turbine speed. The red dots mark the conditions where the SOFC temperature emulator is not in



(a) Air inlet temperature (b) Air inlet pressure (c) Air mass flow

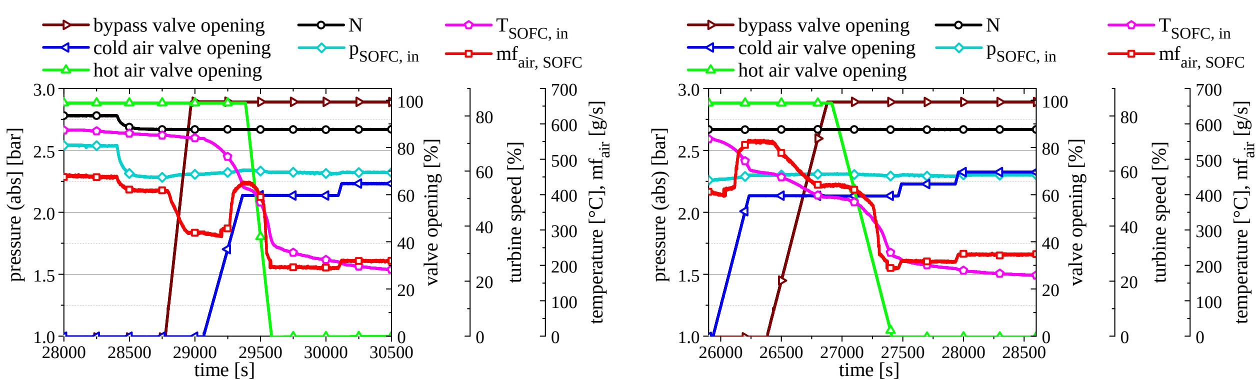
Fig. 7 SOFC inlet conditions

operation and are therefore considered as ”cold conditions”. By contrast, the other points represent different SOFC outlet temperatures. The air temperature (Fig. 7a) at the inlet strongly depends on the load point and varies between 540 °C and 580 °C in cold conditions. Compared to the measurement with SOFC temperature emulation, it is clearly visible that there must be a mutual interaction of the SOFC outlet to the SOFC inlet. This interaction is specific to the construction of the hybrid power plant test rig and is a consequence of the type of connection of the subsystems. The MGT is coupled via an interface to the piping system [8]. The interface itself is a multilayer piping system. The MGT combustor is implemented in the inner pipe. The air mass flow from the recuperator is directed in an annular gap around the combustion chamber and then fed to the piping system. At the inner tube, depending on the MGT combustor inlet temperature, heat is transferred to the fresh air. A SOFC outlet temperature of approximately 790 °C effects the air inlet temperature to about 35 °C at 75 % turbine speed. This interaction has to be taken into account for the operational concept. The pressure at the inlet shows a dependency on the turbine speed but is only slightly effected by the SOFC operation. A minor increase in pressure is seen for higher SOFC outlet temperatures. Within the operational area, the pressure varies from 2.3 bar to 3.12 bar. The air mass flow shows the same behavior as the pressure. At 75 % turbine speed an air mass flow of 415 g/s is provided and at 90 % turbine speed 528 g/s, are provided.

3.4 Shutdown

For the shutdown of the hybrid power plant, first the SOFC has to be shutdown by reducing and finally stopping the electrical load. To prevent damage to the anode side, due to oxidation, it has to be purged with forming gas. It is important to cool down the SOFC carefully, without exceeding the maximum allowed temperature gradients of approximately 5 K/min. During the cooling procedure, the MGT remains in operation to provide the required air mass flow and inlet temperature. When a non critical SOFC system temperature is reached the MGT can be stopped.

Cooling of SOFC The cooling method is similar to the SOFC heating. In general, the same paths are used. On the contrary, for this purpose, different combinations of paths are conceivable. In Fig. 8, two possibilities are plotted against time. Similar to the heating procedure, no well designed control loop for the air mass flow and temperature management was implemented. The main focus was set on the feasibility of such a operation with the available paths. Both methods are carried out at a constant turbine speed of 75 %, the minimum steady state load point. In Fig. 8a, first the bypass path is opened. This has



(a) Cooling of SOFC, path combination 1

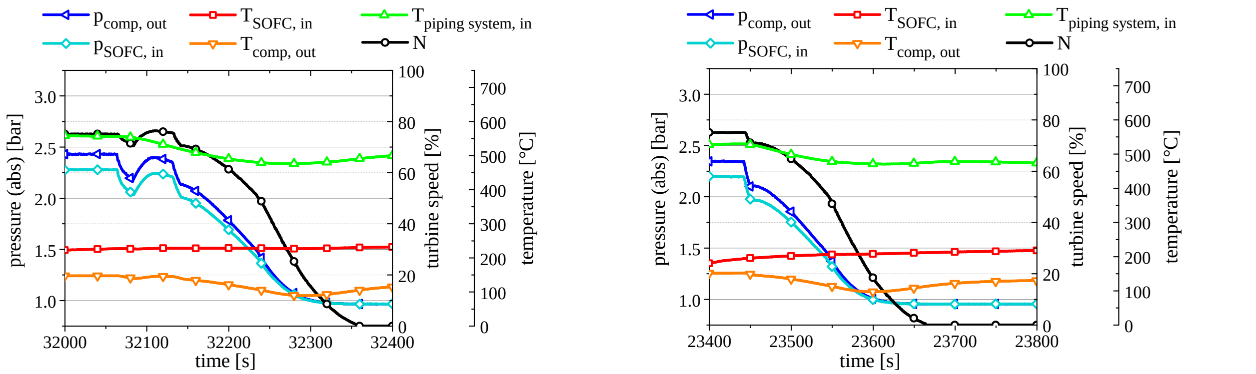
(b) Cooling of SOFC, path combination 2

Fig. 8 Cooling of SOFC using different paths

no major effect on the inlet temperature of the SOFC, but reduces the air mass flow. The subsequent opening of the cold-air path again increases the mass flow to a slightly higher level, as in the operational point. Hereby, a major reduction is seen in the inlet temperature to the SOFC. For the opening of the cold-air path, the same limitations as during SOFC heating have to be applied and the maximum opening is reached at 70 %. The closing of the hot-air path additionally reduces the inlet temperature, however, it also reduces the air mass flow. The pressure changes are slightly, depending on the pressure loss of different path combinations, without fluctuations or instabilities. The changes of the air mass flow are not favorable and have to be smoothed. Another possibility to cool the SOFC is illustrated in Fig. 8b. Here, the method starts by opening the cold air path. The mass flow is increased greatly and the temperature at the inlet decreases. The opening of the bypass path reduces both the temperature and the air mass flow. By closing the hot air path, a drop in the two parameters occurs.

Summarizing, the two possibilities, an enhanced trend could be reached with a combination of bypass and cold-air opening in the beginning. Thus, a stable air mass flow could be achieved while the temperature decreases. As for the heating procedure, the feasibility of cooling the SOFC could be demonstrated. The only limitation was seen in the limited opening of the cold-air valve due to temperature restrictions. Therefore, the possibility of TOT variation should also be taken into account. As the TOT can be significantly reduced in the DLR test rig, this gives opportunity to further optimize the method. Lowering the TOT on the hot-air path decreases the temperature in the hot-air path and therefore, at the inlet to the SOFC. For operation on the cold-air path, this would allow higher flow rates as the temperature at the recuperator outlet decreases. However, a reduction in TOT significantly reduces the electrical power output of the MGT. Since this operation is part of the power plant shutdown procedure, a high electrical power output from the MGT is not an important requirement. Nevertheless this correlation has to be investigated in future measurement campaigns.

Shutdown of MGT For the shutdown of the MGT, it was decided to thermally decouple both subsystems, SOFC and MGT, similar to the start-up process. The approach of a thermally coupled method with a minimum air mass flow through the SOFC has to be considered for further investigations. The procedure starts at 75 % turbine speed. In general, it begins with closing the fuel valve to the MGT combustor and breaking the shaft depending on actual speed and power electronic parameters. During the measurement campaign, a further influencing factor was identified. In Fig. 9, two different shutdowns are plotted against time. The difference between both procedures is the adjusted TOT in the steady state load point before executing



(a) Stop of MGT starting at 75 % turbine speed and TOT = 600 °C

(b) Stop of MGT starting at 75 % turbine speed and TOT = 550 °C

Fig. 9 MGT shutdown

the stop procedure. In the first case (Fig. 9a), the TOT was set to a value of 600 °C. In the second case (Fig. 9b), the TOT was set to 550 °C. Both shutdown procedures start with a sudden drop in turbine speed, accompanied by a drop in pressure and air mass flow caused by the extinguished flame in the combustion chamber. In the first case, at a high TOT, the shaft accelerates again before it is braked through the generator. This causes a variation in system pressure that is not desirable for the pressure control in the SOFC. The first pressure drop is about 0.24 bar in 20 seconds, followed by an increase to nearly the same level. After 30 seconds the second pressure drop occurs before the MGT rolls out smoothly. The temperature at the SOFC is not affected by the MGT stop as it is decoupled. The temperature at the inlet to the piping system decreases approximately 80 °C. The same is seen at the compressor outlet, where the temperature is changing from 145 °C to 90 °C. In the second case, there is only one pressure drop of 0.24 bar within 8 seconds. Although this seems to be much faster, the pressure gradient at the beginning is comparable. After the drop, the shaft is braked smoothly without any acceleration. The temperature at the inlet of the piping system is already on a lower level and therefore, the temperature decrease during shutdown is lower. At the compressor outlet, the temperature decreases from 152 °C to 97 °C and rises again to 130 °C.

Consequently, additional investigations on lower turbine outlet temperatures are necessary.

3.5 Limitations and Emergency Situations

In [7] it was shown that during some transient operations, instabilities occur and emergency operations have to be applied. It was seen that during a load change at higher turbine speed, strong fluctuations in the relative pressure are visible. The relative pressure loss was identified as an indicator for unstable conditions and is defined as:

$$\Delta p_{rel} = \frac{p_{comp\ out} - p_{turb\ in}}{p_{comp\ out}} \tag{1}$$

With the application of the emergency method "bleed-air blow-off", it was possible to stabilize to the load point again. During bleed-air blow-off, the bleed-air valve located at the compressor outlet is opened to direct a defined amount of air out of the system directly into the chimney. Thus, the back-pressure downstream of the compressor is reduced, the compressor is forced to a slightly different load point and the surge margin is increased. For the assessment of the influence of the instabilities on the SOFC inlet conditions, the operation is now analyzed briefly. In Fig. 10, a load change procedure from 87.5 % to 90 % turbine speed is plotted against time. During the load change, sudden fluctuations in the relative pressure loss occur. Analyzing the pressure at the compressor outlet and turbine inlet, indicate that they are caused by fluctuations at the turbine inlet, inside the combustion chamber. A change in fuel mass flow at the main combustor leads to the observed fluctuations. Such fluctuations may lead to a flame out and subsequently, to a shutdown of the MGT, or in worst case, to a surge. Hence, the bleed air valve was opened to a bleed-air mass flow of approximately 60 g/s. This causes a change in

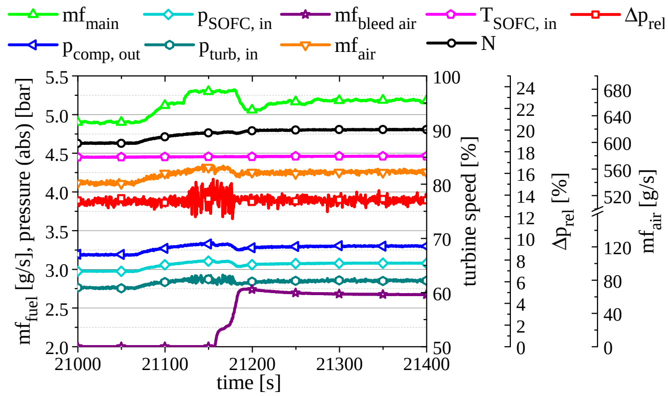


Fig. 10 Instabilities during MGT load change

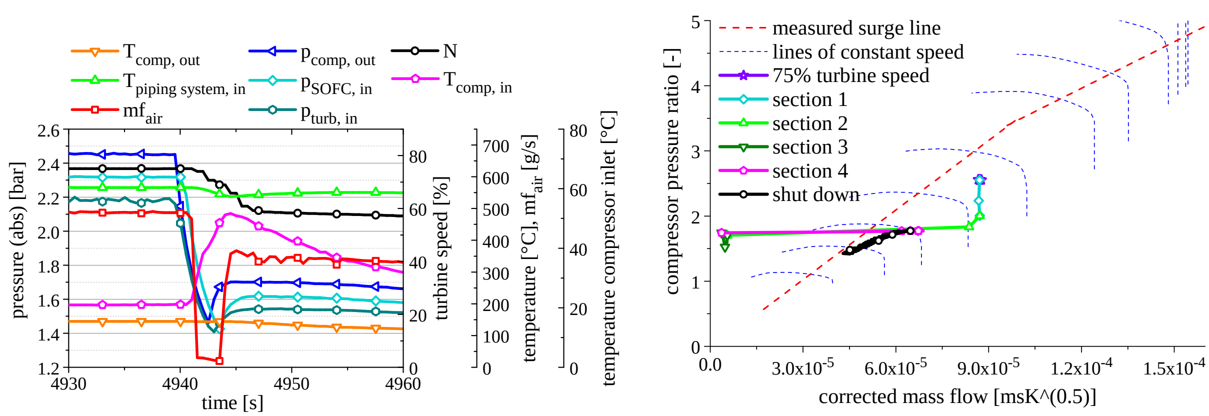
the operational point and stabilizes the combustion again. It is seen that the fluctuations itself do not affect the SOFC in pressure, temperature or air mass flow. The bleed-air method leads to a slight change in pressure and mass flow. Therefore, instabilities in the combustion chamber can be mitigated successfully without major effects on the SOFC.

As mentioned before, a surge event is a major emergency event and has to be prevented. In this section, such an event as shown in Fig. 11, is analyzed in terms of the impact on the SOFC. Fig. 11a shows the trend of the pressure in the system, the temperatures at compressor inlet, outlet and in the piping system as well as the turbine speed and air mass flow. In Fig. 11b, the compressor map of the Turbec T100 is shown. The surge line was measured by Zanger et. al. [13]. In the compressor map, the compressor pressure ratio is plotted against the corrected mass flow. In order to be conform to the measurements of Zanger et. al., the following definitions for pressure ratio and corrected mass flow are used:

$$\Pi_{comp} = \frac{p_{comp\ out}}{p_{comp\ in}} \tag{2}$$

$$x_i = \frac{mf_{air}}{p_{comp\ in}} \cdot \sqrt{T_{comp\ in}} \tag{3}$$

In the compressor map, the different sections of the surge event are marked in different colors. The surge event occurred using the bypass path after a MGT hot-start-up when the hot-air path was opened. The proper reason for the surge is not clearly understood. It is likely that a flame out in the MGT combustion chamber led to the surge. The position of the load point



(a) Surge event plotted against time

(b) Surge event in the compressor map

Fig. 11 Surge event

in the compressor map shows a sufficient surge margin (purple point). A sudden pressure drop occurs in the system. The pressure difference between compressor outlet and turbine inlet drops to zero (section 1). The further decrease in pressure is overlain by the drop of the air mass flow (section 2). The air mass flow shortly remains on a low level (section 3). Due to the measurement of the air mass flow with flow rate sensors, it is not possible to decide if negative mass flow occurs as a back-flow cannot be detected. The temperature at the inlet of the compressor shows a flow reversal as the temperature increases to approximately 60 °C. In section 4, the system pressure rises and the pressure difference between compressor and turbine appears again, however the MGT control system already started the shutdown procedure due to disturbances (beginning shutdown marked in black). The temperature shows no critical gradients. The resulting pressure drop in the SOFC from 2.3 bar to 1.43 bar within 3 seconds would lead to a destruction of the SOFC. This event raises the question how to prevent such surge events. On this topic, further investigations on indicators that a surge is likely will need to be performed. One possibility could be to monitor the compressor outlet with a high speed acoustic sensor to distinguish at early stage indications for a surge.

3.6 Emergency Maneuver

The use of the bleed-air blow-off as an emergency operation was described in the previous section. In this case, the operation was executed with no major impact on the inlet conditions to the SOFC. But in [7] it was demonstrated that the bleed-air blow-off can have an influence on the MGT, if for example, the gradient of the valve opening was too high or the amount of bleed-air mass flow exceeds a certain limit. For the investigation of the influence on the SOFC, the operation is shown in Fig. 12. The MGT is operated in a load point at 90 % turbine speed and a TOT of 645 °C. The bleed air valve is

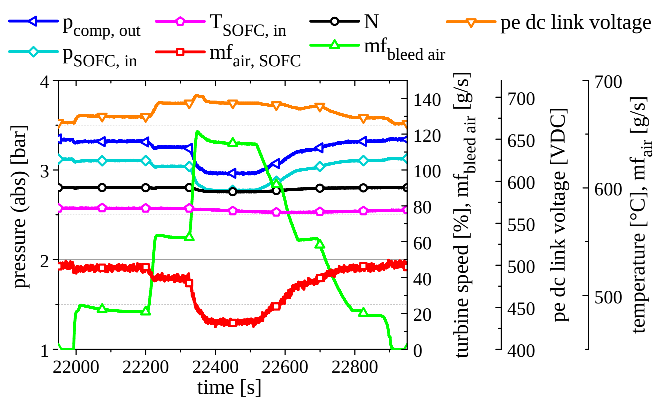


Fig. 12 Stepwise bleed-air opening and closing at 90 % turbine speed

opened stepwise to three different mass flow levels. During the increase to a mass flow of 20 g/s, a decrease in pressure of 0.03 bar and in air mass flow of approximately 5 g/s is seen. The SOFC inlet temperature is not affected. An increase in bleed-air mass flow to 62 g/s shows a Δp of 0.07 bar and Δmf of 10 g/s. During the mass flow increase, small disturbances in the turbine speed are visible. In addition, in the diagram, the PE DC link voltage is plotted in orange. This parameter is linked to the power electronic. The value must not exceed 693 VDC, otherwise the power electronic would be damaged. In the third step, the bleed-air mass flow of 114 g/s leads to an overshoot in the PE DC link up to 700 VDC. Therefore, the MGT control system decelerates the shaft to a turbine speed of 87.7 %, where the limit of 693 VDC is reached again. The increase of mass flow through the bleed-air path, in combination with a turbine speed decrease, leads to a significant pressure and mass flow drop of 0.28 bar and 40 g/s. The temperature at the SOFC inlet also slightly decreases. If the bleed-air valve is closed again, the reverse trend occurs. This example demonstrates that even with emergency operations, the impact on the SOFC has to be taken into account. The required bleed-air mass flow to prevent an emergency has to be balanced against the impact on the SOFC. Of course to prevent against a surge event the impact is only secondary.

4 Summary and Conclusions

The paper shows a brief characterization of the impact of all transient operations on the inlet conditions to the SOFC. A concept for start-up of the hybrid power plant system was described, consisting of the separated MGT start-up and the heating procedure of the SOFC. During the operations, the pressure, temperature and mass flow gradients were analyzed. The operation itself was discussed and an optimization was suggested. It provides to couple MGT and SOFC thermally and mechanically through the whole operation to ensure a minimum air mass flow through the SOFC at all operation conditions. A new concept for the heating method of the SOFC in different start-up phases of the MGT is proposed. The concept foresees the operation of valves and flaps for the regulation of the different paths during SOFC heating process. It could also be shown that the procedure load change is a non-critical operation. Slight changes in the gradients are suggested. The shutdown can be done in the same manner as the start-up. The shutdown of the MGT was analyzed regarding pressure, temperature and mass flow gradients. It was demonstrated that the lowering of the TOT is a possibility to optimize the system shutdown. Moreover, the TOT reduction is suitable for the cooling of the SOFC as it first reduces the temperature on the hot-air path. Secondly, it enlarges the use of cold-air. The cold-air mass flow is limited due to a limit at the recuperator exhaust outlet of the MGT. Here, a lower TOT prevents components downstream of the recuperator from over temperature. Instabilities in the combustion chamber due to a load change could be successfully stopped with the use of bleed-air blow-off. Only a minor impact on the SOFC was observed. Nevertheless, situations may occur that may lead to damage of the SOFC. As an example, a surge event was analyzed. Finally, the limitations in the bleed-air blow-off were characterized. The analysis and discussion of the different operations provide an optimized control concept for the hybrid power plant test rig at the DLR, which needs to be further validated in a future measurement campaign.

Acknowledgements

The authors would like to thank Martin Stärk and Timo Lingstädt for the fruitful discussions and the support during the measurement campaigns. Furthermore, the support from the German Federal Ministry of Economic Affairs and Energy for the project ”SyHyKW” is gratefully acknowledged. (Support code: 03ET2018).

References

[1] Pierre, J. F., 2008. High temperature solid oxide fuel cell generator development, final technical progress report. Tech. Rep. DOE Cooperative Agreement No. DE-FC26-97FT34139, Siemens Power Generation Stationary Fuel Cells George Westinghouse Science and Technology Center 1310 Beulah Road Pittsburgh, PA 15235-5098.

[2] Roberts, R., and Brouwer, J., 2006. "Dynamic simulation of a pressurized 220kw solid oxide fuel-cell–gas-turbine hybrid system: modeled performance compared to measured results". *Journal of fuel cell science and technology,* **3**(1), pp. 18–25.

[3] Yi, Y., Smith, T. P., Brouwer, J., Rao, A. D., and Samuelsen, G. S., 2003. "Simulation of a 220 kw hybrid sofc gas turbine system and data comparison". In Proceedings-Electrochemical Society, Electrochemical Society, pp. 1442–1454.

[4] Veyo, S. E., 2003. "Tubular sofc hybrid power systems". In Third DOE/UN International Conference and Workshop on Hybrid Power Systems.

[5] Hohloch, M., Widenhorn, A., Lebkuechner, D., Panne, T., and Aigner, M., 2008. "Micro gas turbine test rig for hybrid power plant application". In ASME Turbo Expo 2008: Power for Land, Sea, and Air, GT2008-50443.

[6] Hohloch, M., Zanger, J., Widenhorn, A., and Aigner, M., 2010. "Experimental characterization of a micro gas turbine test rig". In ASME Turbo Expo 2010: Power for Land, Sea, and Air, GT2010-22799.

[7] Hohloch, M., Huber, A., and Aigner, M., 2014. "Experimental investigation of a sofc/mgt hybrid power plant test rig: Impact and characterization of coupling elements". In ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, GT2014-25918.

[8] Hohloch, M., Huber, A., and Aigner, M., 2016. "Experimental investigation of a sofc/mgt hybrid power plant test rig: Impact and characterization of a fuel cell emulator". In ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, GT2016-57747.

[9] Tucker, D., Lawson, L., and Gemmen, R., 2005. "Characterization of air flow management and control in a fuel cell turbine hybrid power system using hardware simulation". In ASME 2005 Power Conference, American Society of Mechanical Engineers, pp. 959–967.

[10] Pascenti, M., Ferrari, M. L., Magistri, L., and Massardo, A. F., 2007. "Micro gas turbine based test rig for hybrid system emulation". In ASME Turbo Expo 2007: Power for Land, Sea, and Air, American Society of Mechanical Engineers, pp. 7–15.

[11] Panne, T., Widenhorn, A., and Aigner, M., 2008. "Steady state analysis of a sofc/gt hybrid power plant test rig". In ASME Turbo Expo 2008: Power for Land, Sea, and Air, GT2008-50288.

[12] Panne, T., Widenhorn, A., Boyde, J., Matha, D., Abel, V., and Aigner, M., 2007. "Thermodynamic process analyses of sofc/gt hybrid cycles". In 5th International Energy Conversion Engineering Conference and Exhibit (IECEC), St. Louis, MO, June, pp. AIAA 2007–4833.

[13] Zanger, J., Widenhorn, A., and Aigner, M., 2011. "Experimental investigations of pressure losses on the performance of a micro gas turbine system". *Journal of Engineering for Gas Turbines and Power, J Eng Gas Turb Power,* **133**(8), p. 082302.